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SOIL CARBON DIOXIDE FLUXES FOLLOWING TILLAGE IN SEMIARID MEDITERRANEAN AGROECOSYSTEMS

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Abstract

In semiarid Mediterranean agroecosystems, low and erratic annual rainfall together with the widespread use of mouldboard ploughing (conventional tillage, CT), as the main traditional tillage practice, has led to a depletion of soil organic matter (SOM) and with increases in CO_2 emissions from soil to the atmosphere. In this study, we evaluated the viability of conservation tillage: RT, reduced tillage (chisel and cultivator ploughing) and, especially, NT (no-tillage) to reduce short-term (from 0 h to 48 h after a tillage operation) and mid-term (from 0 h to several days since tillage operation) tillage-induced CO_2 emissions. The study was conducted in three long-term tillage experiments located at different sites of the Ebro river valley (NE Spain) across a precipitation gradient. Soils were classified as: Fluventic Xerocrept, Typic Xerofluvent and Xerollic Calciorthid. Soil temperature and water content were also measured in order to determine their influence on tillage-induced CO_2 fluxes. The majority of the CO_2 flux measured immediately after tillage ranged from 0.17 to 6 g CO_2 m^{-2} h^{-1} and was from three- to fifteen-times greater than the flux before tillage operations, except in NT where soil CO_2 flux was low and steady during the whole study period. Mid-term CO_2 emission showed a different trend depending on the time of the year in which tillage was implemented. Microclimatic soil conditions (soil temperature and water content) had little impact on soil CO_2 emission following tillage. In the semiarid Mediterranean agroecosystems studied, NT had low short-term soil CO_2 efflux compared with other soil tillage systems (e.g. conventional and reduced tillage) and therefore can be recommended to better manage C in soil.

***Keywords**:* Tillage, Soil CO_2 fluxes, No-tillage, Mediterranean agroecosystems

1. Introduction

Land-use change and soil cultivation have led to a depletion of soil organic matter (SOM) content (Paustian et al., 1997; Lal, 2004). Loss in SOM content has been associated with a reduction in soil productivity (Bauer and Black, 1994) and with an increase in CO_2 emission from soil to the atmosphere (Paustian et al., 1998; Schlesinger, 2000).

Soil CO_2 produced by microbial decomposition is stored in soil pores and emitted to the atmosphere mainly by a process of diffusive transport due to concentration gradients (Rolston, 1986). However, this process is altered during tillage when an increase in soil CO_2 flux occurs (Reicosky and Lindstrom, 1993; Prior et al., 1997; Reicosky et al., 1997; Ellert and Janzen, 1999; Alvarez et al., 2001). Roberts and Chan (1990), who observed an increase in soil CO_2 emission after a simulated tillage experiment, concluded that greater microbial respiration was not the main reason for soil organic carbon (SOC) loss after tillage. Later, Reicosky and Lindstrom (1993) related the increase in CO_2 flux observed in various tillage systems with different soil roughness and tillage intensity. Reicosky et al. (1997), measuring CO_2 fluxes and soil inorganic N after tillage, did not find a clear relationship between high CO_2 flux after tillage and an increase of inorganic N. Therefore, they concluded that the increase in CO_2 flux immediately after tillage (short-term) was the result of a physical release of CO_2 entrapped in soil pores from previous microbial activity rather than changes in microbial activity at the time of tillage. Besides this *burst* effect on soil CO_2 flux, tillage also accelerates SOM decomposition. Tillage contributes to the mixing of new fresh residue with soil, modifying soil profile characteristics (e.g., aeration, moisture and temperature regimes) and promoting soil microbial activity (Doran, 1980; Reicosky et al., 1995; Peterson et al., 1998). At the same time, tillage promotes macroaggregate turnover exposing protected SOM to soil microorganisms (Six et al., 1998, 1999).

Several studies have observed greater CO_2 flux under conventional tillage compared with no-tillage during several days following tillage presumably due to stimulatory effect of tillage on soil microbial activity (Reicosky, 1997; Dao, 1998; Rochette and Angers, 1999; Alvarez et al., 2001). Rochette and Angers (1999), measuring CO_2 flux during several days after fall, spring and summer mouldboard ploughing, observed that soil microclimatic conditions following tillage events played an important role in CO_2 emission.

Semiarid dryland agroecosystems of the Ebro river valley (north eastern Spain) are characterised by low and erratic annual rainfall and by high evapotranspiration and, as a consequence, by low crop yield and crop residue production. These features, together with the traditional widespread use of mouldboard ploughing as the main tillage operation, have led to low SOC content in this region. Since there is no previous information about the influence of tillage practices on short-term soil CO_2 fluxes in Mediterranean semiarid agroecosystems, we hypothesized that short-term soil CO_2 emissions may be reduced by the adoption of conservation tillage practices, especially with no-tillage, as it was found in similar experiments carried out in other semiarid areas (Kessavalou et al., 1998; Ellert and Janzen, 1999).

Knowledge about the influence of tillage practices on soil CO_2 flux is essential in order to establish strategies to help mitigate greenhouse gases emissions, especially in these Mediterranean semiarid agroecosystems where there is no information about the influence of tillage practice on short-term soil CO_2 flux.

The objectives of this study were to *(i)* quantify the short-term and mid-term impacts of tillage on soil CO_2 flux following different tillage systems, and *(ii)* determine the influence of soil microclimatic conditions, site and time of ploughing on short-term soil CO_2 flux.

2. Materials and methods

2.1. Sites, tillage and cropping systems

The experiment was conducted over a 2-yr period from March 2003 to March 2005 at three different long-term tillage experiments located across the Ebro river valley (NE Spain). These sites were chosen due to differences in soil, climate and technology conditions. The Selvanera and Agramunt experimental sites, established in 1987 and 1990, respectively, were located in the Lleida province at dryland farms managed by the Agronomy Group of the University of Lleida. The third experimental site, Peñaflor, was established in 1989 at the dryland research farm of the Estación Experimental Aula Dei (Consejo Superior de Investigaciones Científicas) in the Zaragoza province. More details on the experimental sites and soils are given in Table 1. Monthly precipitation and mean monthly air temperature recorded at the experimental sites for the study period are presented in Table 2.

In Selvanera (SV), three tillage treatments were compared: conventional tillage (CT), subsoil tillage (ST) and no-tillage (NT). The CT treatment consisted of a deep subsoil tillage to a depth of 40 cm. The ST consisted of subsoil tillage to a depth of 25 cm. The subsoiler consisted of three 4-cm wide shanks spaced 35 cm apart. Unlike in the other experimental sites, mouldboard ploughing was not used in this site. In SV, the cropping system was a wheat (*Triticum aestivum* L.)-barley (*Hordeum vulgare* L.)-wheat-rapeseed (*Brassica napus* L.) rotation and tillage was implemented in July-August. In Agramunt (AG), four tillage treatments were compared: conventional tillage (CT), subsoil tillage (ST), reduced tillage (RT) and no-tillage (NT). The CT treatment consisted of a mouldboard ploughing operation to a depth of 25-30 cm. The mouldboard plough consisted of three bottoms of 0.50 m width. The ST treatment consisted of a subsoiler pass to a depth of 25 cm. The subsoiler had the same characteristics as that used in the SV site. The RT treatment consisted of a cultivator pass to a depth of 15 cm. The cultivator consisted of 11 flexible shanks spaced 19.5 cm apart. In Agramunt, the cropping system consisted of a barley-wheat rotation and tillage was implemented in November. In Peñaflor (PN), three tillage treatments (CT, RT and NT) were compared under both the traditional cereal-fallow rotation (PN-CF) and under continuous cropping (PN-CC) with barley. In the CC system, the CT treatment consisted of mouldboard ploughing to a depth of 30-40 cm in November as primary tillage. The mouldboard plough had the same characteristics as that used at AG. The RT treatment was implemented also in November by chisel ploughing to a depth of 25-30 cm. The chisel plough consisted of 5 rigid shanks spaced 20 cm apart and with a shank width of 5 cm. In the NT treatment sowing was with a disc drill at SV and AG sites and with a hoe type planter at the PN site. In NT plots, soil was kept free of weeds by spraying glyphosate.

In PN-CC 2003, seven days after primary tillage, a pass with a rotovator was performed as secondary tillage in the CT and RT treatments. No secondary tillage was implemented in PN-CC 2004. In the PN-CF rotation, primary tillage was carried out in late winter (March) using the same implements and ploughing depths as in PN-CC. No secondary tillage was performed in PN-CF. In PN-CF 2003 and PN-CF 2005, mouldboard ploughing in the CT plots was followed by a pass with a tractor mounted scrubber consisting of a metal beam passed over the soil surface in order to break down large clods.

At all three sites tillage operations began at the same time (09:00 h GMT+1). Plots were arranged in a randomized complete block design with three replicates at SV and PN and with four replicates at AG. At each site, a whole measurement sequence took about 2 h. The plot size was 50 m x7 m at SV, 50 m x 9 m at AG and 33 m x10 m at PN.

2.2. Experimental measurements

2.2.1. Soil CO_2 flux

Soil CO_2 flux was measured using a dynamic chamber system (model CFX-1, PPSystems, Hertfordshire, London) connected to an infrared gas analyzer (model EGM-4, PPSystems, Hertfordshire, London). This system was based on the chamber designed by Rayment and Jarvis (1997), which was developed to ensure that atmospheric pressure fluctuations were transferred through to the soil surface. Soil CO_2 flux was calculated from the difference in CO_2 concentration between air entering and leaving the chamber. The chamber had a cylindrical diameter of 21 cm, covering a soil surface of 346 cm^2. Flow rate was adjusted to 900 mL min^{-1}. Each plot was divided into two regions and a measurement per region was taken each time. The chamber was inserted 3 cm into the soil to prevent CO_2 leakage to the atmosphere. Flux readings were taken 3 minutes after the chamber was inserted into the soil in order to avoid possible unrealistic values caused by the disturbance produced after placing the chamber into the soil (Pumpanen et al., 2004).

Short-term soil CO_2 flux was measured during eight different tillage events between March 2003 and March 2005. In all experimental fields, soil CO_2 flux was determined several times from 24 h prior to tillage to 48 h after each tillage operation. Table 3 shows the times of measurements and dates of tillage operations during all experimental periods. In addition, in both PN-CC 2003 and PN-CF 2003, soil CO_2 flux was measured up to 8 and 18 days after the first tillage event, respectively. The idea of extending the measurement period was aimed to study the effect of tillage on soil CO_2 emission beyond 48 h after the tillage operation. In order to make easier interpretation and discussion of the data shown in this study, we considered short-term soil CO_2 flux as that measured from 24 h prior to tillage to 48 h after tillage and mid-term soil CO_2 flux as that measured from 24 h prior to tillage to 8 and 18 days after tillage operation.

2.2.2. Soil temperature and moisture content

Soil temperature was measured with a hand-held probe (model STP-1, PPSystems, Hertfordshire, London) which was inserted 5 cm into the soil 5 cm away from the edge of the CO_2 chamber. A soil temperature value was recorded at the same time as the soil CO_2 flux was recorded.

Likewise, with each CO_2 measurement a soil-surface sample was collected to a depth of 5 cm to determine the gravimetric soil water content by oven drying the soil at 105 ºC.

Soil temperature and soil water content were measured prior to tillage, immediately after tillage and 24 h and 48 h after tillage.

Daily air temperature and precipitation observations were made at the experimental sites using automated weather stations.

Statistical analyses of data were performed using SAS (SAS Institute, 1990). Analyses of variance was applied to compare tillage treatments and differences between means were tested with the Duncan's multiple range test. Regressions analysis was used to determine the relationship of soil CO_2 flux to soil temperature and soil water content.

3. Results and discussion

3.1. Tillage effects on short-term soil CO_2 flux

A significant increase in CO_2 flux was observed immediately after tillage operations in all tillage treatments, except NT (Figs. 1 and 2). These CO_2 peaks just after tillage were the greatest in all the study periods and ranged from 0.17 g CO_2 m^{-2} h^{-1} under RT in PN-CF 2003 to 13 g CO_2 m^{-2} h^{-1} under CT in AG 2003 with more than the 90% of observations was in the range of 0.17 to 6 g CO_2 m^{-2} h^{-1}. Kessavalou et al. (1998) in a semiarid wheat-fallow system of Nebraska found CO_2 flux nearly 1 g CO_2 m^{-2} h^{-1} immediately after subtilling. Rochette and Angers (1999), after mouldboard ploughing, measured CO_2 flux between 1.3 and 3.2 g CO_2 m^{-2} h^{-1}. Reicosky et al. (1997), comparing mouldboard ploughing and chisel ploughing with NT in a continuous sorghum (*Sorghum bicolor* L.) system and using a vented chamber covering a soil surface of 0.1 m^2, obtained CO_2 flux after tillage that ranged between 0.7 and 2.2 g CO_2 m^{-2} h^{-1}. However, in the same experiment, using a canopy chamber covering 2.71 m^2, the flux varied from 16 to

22 g CO_2 m^{-2} h^{-1}. Several authors have compared different CO_2 measuring techniques remarking about the variability of the values obtained among them (Rochette et al. 1992; Rayment, 2000; Pumpanen et al., 2004).

Reicosky and Lindstrom (1993) and Reicosky et al. (1997) concluded that the increase in CO_2 flux after tillage was due to the physical release of the CO_2 entrapped and accumulated in soil pores from previous microbial activity. Rochette and Angers (1999) used the term *degassing* to designate this increase in CO_2 emission immediately following a tillage operation, resulting from changes in the physical characteristics of tilled soils. According to these authors, degassing implies a passive loss of stored CO_2 from loosened soil.

On the other hand, Reicosky and Lindstrom (1993) and Prior et al. (2000) suggested that initial CO_2 flux after tillage was also related to the depth and degree of soil disturbance. In our experiment, mouldboard ploughing was the tillage operation with greatest degree of soil disturbance. Thus, in the sites where the CT treatment consisted of a pass of mouldboard plough (AG, PN-CC and PN-CF), CO_2 flux immediately after tillage was greatest (Figs. 1 and 2). In SV, where the CT and ST treatments consisted of a pass with a subsoiler to a depth of 40 and 25 cm respectively, CO_2 flux immediately after tillage was similar (Fig. 1). This result suggests that the lack of soil inversion with subsoiling negated any possible difference in CO_2 flux due to tillage depth.

The initial CO_2 flux peak that followed tillage declined considerably within 3 h of tillage operation, especially with CT (i.e. from 13 to 3 g CO_2 m^{-2} h^{-1} in AG 2003) (Figs. 1 and 2). Reicosky (1997), observed a decrease from 122 g CO_2 m^{-2} h^{-1} to 6 g CO_2 m^{-2} h^{-1} within 2 h after a pass with moldboard plough.

3.2. Effect of tillage on mid-term soil CO_2 flux

In PN-CC 2003 and PN-CF 2003, mid-term CO_2 flux was also studied 8 and 18 days, respectively. CO_2 flux was steady, except following rainfall events and secondary tillage operations (Fig. 3). At 264 h after primary tillage a precipitation event of 27 mm during 23 h with a maximum intensity of 6 mm h^{-1} occurred. This rainfall event which was the only measured during the tillage events studied, induced an increase of 0.10-0.15 g CO_2 m^{-2} h^{-1} in the three tillage treatments (CT, RT and NT). A similar effect was observed in other studies (Prior et al. 1997; Dao, 1998; Ellert and Janzen, 1999; Alvarez et al. 2001). Akinremi et al. (1999) suggested that greater CO_2 flux after a precipitation event was the result of two processes: firstly, a physical release of the CO_2 entrapped in the soil structure and displaced due to water filling of soil pores and, secondly, a stimulation effect on soil microbial activity. A second peak in CO_2 flux was observed under CT at 408 h after tillage and was the result of soil disturbance produced by a tractor mounted scrubber (metal beam) to break up clods and create a smoother soil surface. In PN-CC 2003, only one peak of CO_2 was observed 168 h after primary tillage in the CT and RT plots due to a rotovator pass, producing twofold increase in CO_2 flux (Fig. 3). These findings agree with La Scala et al. (2005) who compared different rotary tillage implements and found twofold increase in CO_2 flux after rotary tillage.

Different CO_2 flux between tilled treatments and NT was observed in PN-CF 2003 (Fig. 3) than in PN-CC 2003 (Fig. 3). As both fields were adjacent and had similar soil characteristics, it appears that the difference was due to the effect of different ploughing dates and climatic conditions after tillage. In PN-CC 2003, CO_2 flux was measured during November when monthly average air temperature was 7 ºC, whereas in PN-CF 2003 data were collected in March-April when the average air temperature was 11 ºC. This greater air temperature in PN-CF together with the rainfall event registered 264 h after tillage created better conditions for soil microbial activity in the tilled treatments (CT and RT) compared to PN-CC. Thus, differences in climatic conditions after tillage can have a strong influence on SOM decomposition and, therefore, on mid-term soil CO_2 emissions (Rochette and Angers, 1999).

3.3. Influence of soil temperature and soil water content on short-term soil CO_2 flux

The lowest soil temperature was observed at the AG and PN-CC fields, since tillage was implemented in November. Soil temperature at 5 cm depth ranged from 3 to 12ºC and from 6 to 10 ºC at AG and PN-CC, respectively (Fig. 4). Greatest soil temperature was measured at SV during summer (Fig. 4), according to the high air temperatures typical at this time of the year (Table 2).

The lowest soil water content was observed in SV 2003, ranging from 0.03 to 0.05 g g^{-1} (Fig. 5). The greatest water content was measured in AG 2003, close to 0.30 g g^{-1}. In PN-CC and PN-CF, a slight decrease in soil water content in the 24 h following tillage was observed in the CT and RT plots (Fig. 5). This finding is in agreement with Moret et al. (2006) from the same experimental plots, in which decreased soil water content in the CT and RT treatments just after tillage was due to an increase in soil water evaporation. Likewise, in SV and AG the greatest soil water content was observed in NT. In the same study area, Lampurlanés et al. (2001) also observed greater water contents in NT and suggested that better infiltration rates in NT promoted greater soil water content as compared with RT and ST.

In general, results indicate that tillage operations had little impact on soil temperature and soil water content. Differences among tillage treatments although small kept steady during the whole measurement period (Figs. 4 and 5). Small changes in surface soil temperature and water content after tillage operations have also been observed by other authors in similar studies (Ellert and Janzen, 1999; Prior et al., 2004). Prior at al. (2004) suggested that small changes in soil water content and temperature did little in helping to interpret differences in CO_2 flux between tillage treatments. In our study, no significant relationships between CO_2 flux and soil temperature and water content were found (Table 4). Only the linear regression for AG 2003 was significant, where soil temperature explained 25% of the variability in CO_2 flux (P <0.1).

A possible explanation for this lack of relationship with CO_2 flux may be related to the fact that soil temperature and water content were only measured to 5 cm depth and soil tillage was implemented to much deeper soil depth. Therefore, a large proportion of the CO_2 flux could come from soil below 5 cm.

3.4. Effect of site and tillage date on soil CO_2 flux

Estimates of cumulative CO_2 flux from 24 h prior tillage to 48 h following each tillage event were calculated using numerical integration (trapezoid rule). This method provided values that could be used to compare fluxes among years, sites and treatments. However, the long time between readings (e.g., 24 h) may be subject to error because it ignores daily temporal trend (Reicosky, 1997).

Difference in CO_2 flux between years for the same site have been related to difference in microbial activity prior to tillage (Reicosky, 1997; Prior et al., 2004). In the present study, differences in CO_2 flux might have resulted from different soil conditions (e.g., soil temperature and soil water content) prior to tillage. Cumulative CO_2 flux was threefold greater in CT for SV 2004 than for SV 2003 (Table 5). As tillage was implemented in summer, air temperature in both study periods was high (>20ºC) (Table 2). However, greater precipitation was recorded from harvest to tillage in 2004 than in 2003 (27.9 mm and 8.4 mm during July 2004 and July 2003, respectively) (Table 2). Therefore, better soil conditions for microbial activity in 2004 than in 2003 probably led to greater CO_2 flux. Likewise, in PN-CC cumulative CO_2 flux was greater in 2003 than in 2004 (Table 5). Although mean air temperature from harvest to tillage was similar in both years (20 and 21ºC in 2003 and 2004, respectively), the precipitation received was higher in 2003 compared with 2004 (Table 2). Greater soil water content during 2003 led to more optimal conditions for microbial activity and, thus, to greater soil CO_2 flux.

Different soil CO_2 flux among sites was the result of both different amount of CO_2 stored within soil pores at tillage and different tillage operations. The CO_2 stored in soil pores have been affected by soil characteristics, soil microclimatic conditions from harvest to tillage, the amount and quality of crop residues and the time elapsed between crop harvest and tillage. Lowest cumulative CO_2 flux found in PN-CF was probably the result of low residue production (1000-2000 kg ha^{-1}), low SOC content (Table 1), low soil temperature prior to tillage and the long time elapsed from harvest to tillage (7-8 months).

4. Summary and conclusions

Soil disturbance by tillage caused an immediate sharp increase in soil CO_2 flux. This was a relatively short process lasting less than three hours from tillage. The amount of CO_2 emitted immediately after tillage was proportional to the degree of soil disturbance produced. Thus, mouldboard ploughing caused a greater CO_2 flux than chisel ploughing at Agramunt (AG) and Peñaflor (PN-CC and PN-CF). At Selvanera, CO_2 flux was similar between CT and ST due to the lack of soil inversion in both treatments. At all sites, soil CO_2 flux under NT was low and kept steady during the whole study period. Microclimatic soil conditions (soil temperature and soil water content) had little impact on soil CO_2 flux following tillage. However, rainfall events following tillage produced an increase in the amount of CO_2 released from soil surface in all tillage treatments studied. Although microbial activity was not measured in this experiment, we hypothesised that differences in cumulative amount of CO_2 emitted among experimental fields and years were generated by different conditions for soil microbial activity from harvest to tillage. In this semiarid area, annual rainfall variability is a major characteristic that has a strong influence on soil microbial activity and, consequently, on differences in CO_2 stored within soil pores between seasons.

In semiarid dryland agroecosystems of the Ebro river valley, mouldboard ploughing increased soil CO_2 flux immediately after tillage as compared to more conservative tillage systems and especially with NT. In this area, the absence of soil disruption with NT has a potential benefit to lower greenhouse gases emission compared with other tillage treatments in which soil is disturbed. We believe that further research is needed to better assess the impact of this decrease in CO_2 emission with the adoption of NT practices.

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Figure captions

Fig. 1. Short-term soil CO_2 flux following tillage operations (CT, conventional tillage; ST, subsoil tillage; RT, reduced tillage; NT, no-tillage) in November 2003 and November 2004 in Agramunt in a barley-wheat rotation (AG 2003 and AG 2004, respectively) and in July 2003 and August 2004 in Selvanera in a wheat-barley-wheat-rapeseed rotation (SV 2003 and SV 2004, respectively). Bars represent LSD ($P<0.05$) for comparison among tillage treatments, where significant differences were found.

Fig. 2. Sort-term soil CO_2 flux following tillage operations (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) in November 2003 and November 2004 in Peñaflor in a continuous barley system (PN-CC 2003 and PN-CC 2004, respectively) and in March 2003 and March 2005 in Peñaflor in a barley-fallow rotation (PN-CF 2003 and PN-CF 2005, respectively). Bars represent LSD ($P<0.05$) for comparison among tillage treatments, where significant differences were found.

Fig. 3. Mid-term soil CO_2 flux in Peñaflor following tillage operations (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) in November 2003 in a continuous barley cropping system (PN-CC 2003) and March 2003 in a barley-fallow rotation (PN-CF 2003). Bars represent LSD ($P<0.05$) for comparison among tillage treatments, where significant differences were found.

Fig. 4. Soil temperature at 5 cm depth during the period of short-term CO_2 flux measurements under different tillage treatments (CT, conventional tillage; ST, subsoil tillage; RT, reduced tillage; NT, no-tillage) at Agramunt in a barley-wheat rotation (AG 2003 and AG 2004), Selvanera in a wheat-barley-wheat-rapeseed rotation (SV 2003 and SV 2004) and Peñaflor in a continuous barley cropping system (PN-CC 2003 and PN-CC 2004) and in a barley-fallow

rotation (PN-CF 2003 and PN-CF 2005). Bars represent LSD (P<0.05) for comparison among tillage treatments, where significant differences were found.

Fig. 5. Gravimetric soil water content in the top 5 cm soil layer under different tillage treatments (CT, conventional tillage; ST, subsoil tillage; RT, reduced tillage; NT, no-tillage) at Agramunt in a barley-wheat rotation (AG 2003 and AG 2004), Selvanera in a wheat-barley-wheat-rapeseed rotation (SV 2003 and SV 2004) and Peñaflor in a continuous barley cropping system (PN-CC 2003 and PN-CC 2004) and in a barley-fallow rotation (PN-CF 2003 and PN-CF 2005). Bars represent LSD (P<0.05) for comparison among tillage treatments, where significant differences were found.

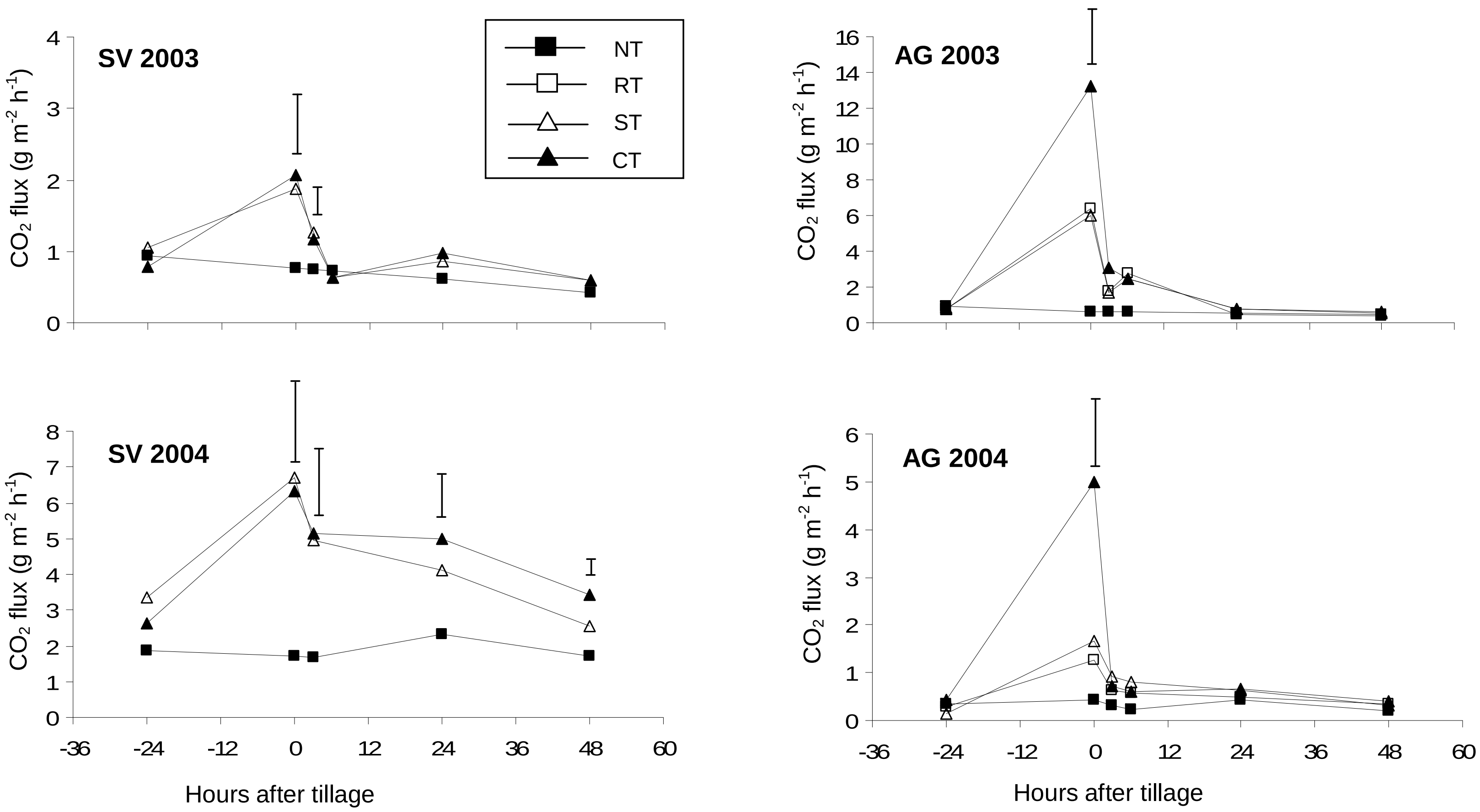
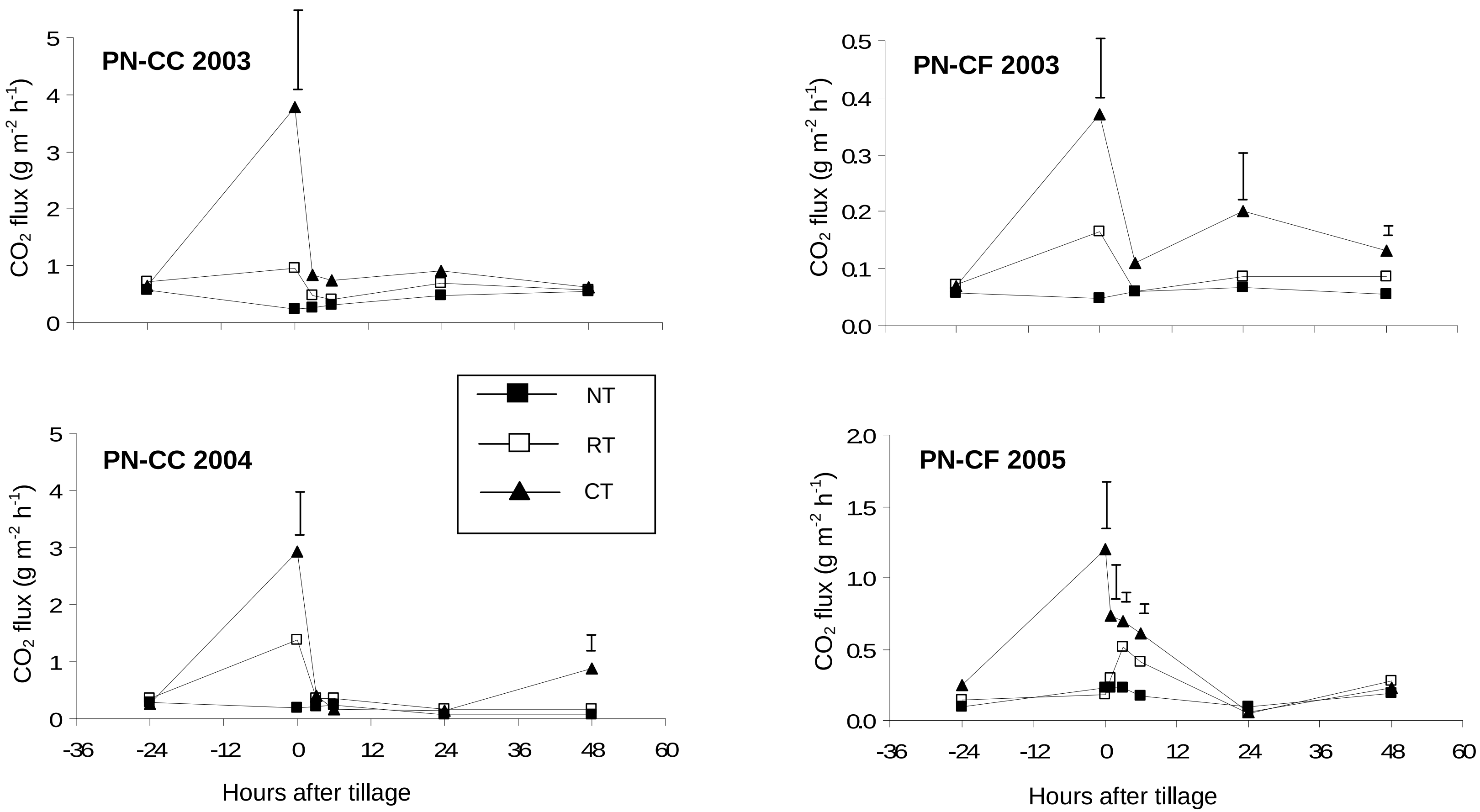

SV 2003
AG 2003
SV 2004
AG 2004
NT
RT
ST
CT
CO2 flux (g m-2 h-1)
Hours after tillage
-36
-24
-12
0
12
24
36
48
60

Fig. 1.



PN-CC 2003
PN-CF 2003
PN-CC 2004
PN-CF 2005
NT
RT
CT
CO2 flux (g m-2 h-1)
Hours after tillage
0
1
2
3
4
5
0.0
0.1
0.2
0.3
0.4
0.5
0.5
1.0
1.5
2.0
-36
-24
-12
12
24
36
48
60

Fig. 2.

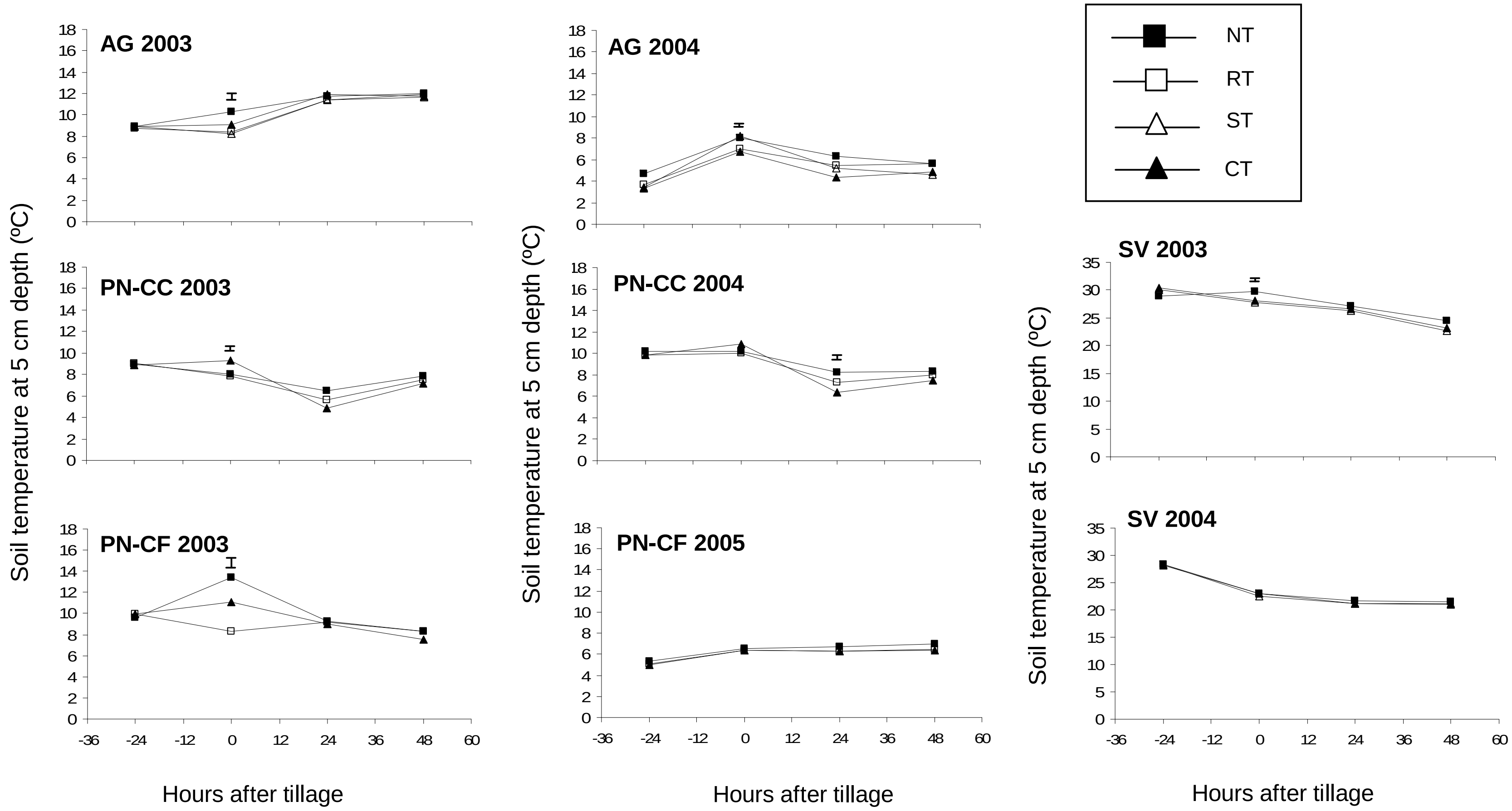

AG 2003
PN-CC 2003
PN-CF 2003
AG 2004
PN-CC 2004
PN-CF 2005
SV 2003
SV 2004
NT
RT
ST
CT
Soil temperature at 5 cm depth (ºC)
Hours after tillage

Fig. 4.

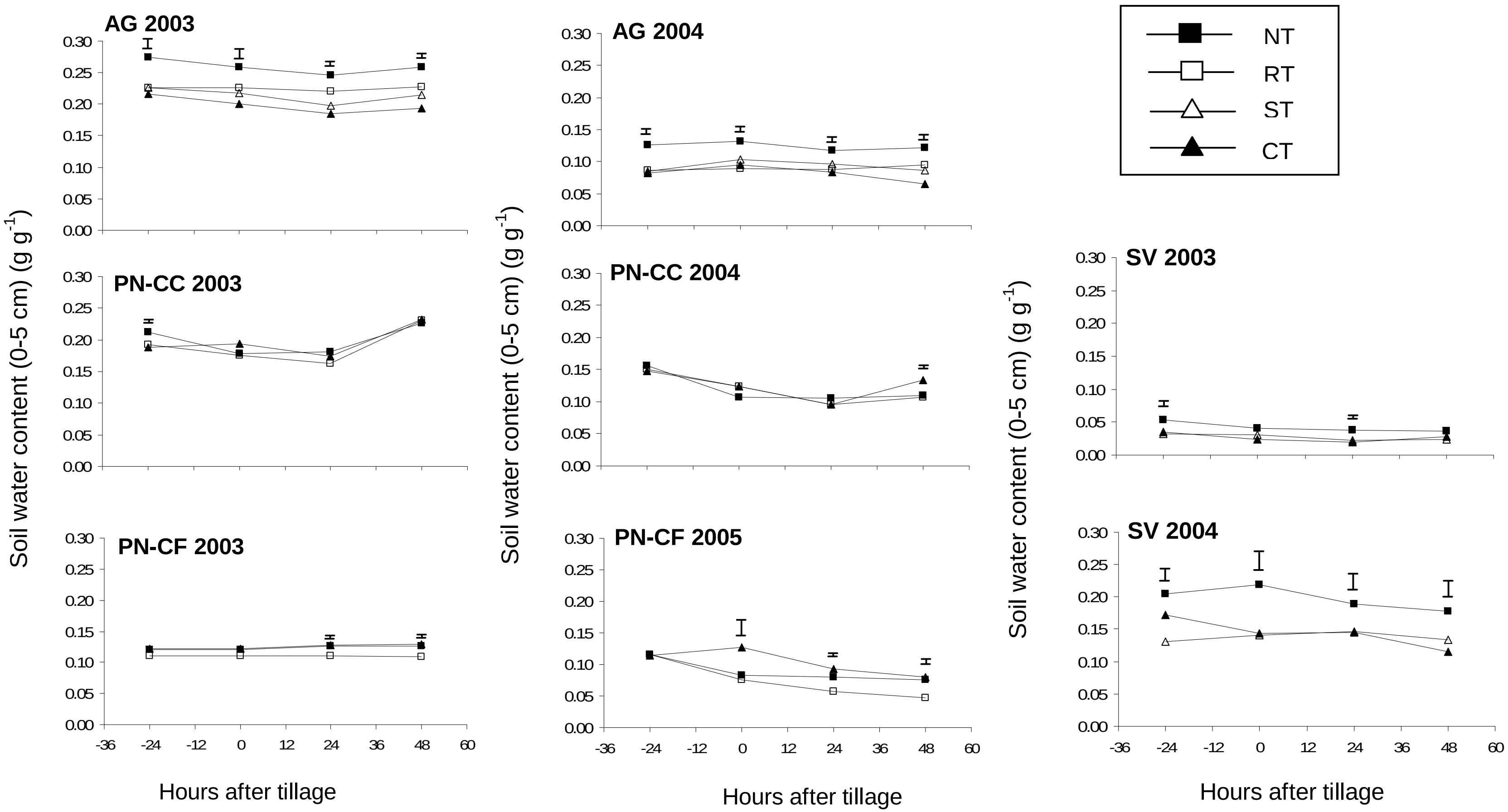

AG 2003
AG 2004
NT
RT
ST
CT
PN-CC 2003
PN-CC 2004
SV 2003
PN-CF 2003
PN-CF 2005
SV 2004
Soil water content (0-5 cm) (g g-1)
Hours after tillage

Fig. 5.

Tables

Table 1. Site and soil (Ap horizon) characteristics.

Climate and soil characteristics	Study sites: Selvanera	Agramunt	Peñaflor	
Latitude	41º 50’N	41º 48’N	41º 44’N	
Longitude	1º 17’E	1º 07’E	0º 46’W	
Elevation (m)	475	330	270	
Mean annual air temperature (ºC)	13.9	14.2	14.5	
Mean annual precipitation (mm)	475	430	390	
Soil classification [¶]	Fluventic Xerocrept	Typic Xerofluvent	Xerollic Calciorthid	
Ap horizon depth (cm)	37	28	30	
pH (H_2O, 1:2.5)	8.3	8.5	8.23	
$EC_{1:5}$ (dS m^{-1})	0.16	0.15	0.29	
Water retention (g g^{-1})				
-33 kPa	0.16	0.16	0.20	
-1500 kPa	0.04	0.05	0.11	
Particle size distribution (%)				
Sand (2000-50 µm)	36.5	30.1	32.4	
Silt (50-2 µm)	46.4	51.9	45.5	
Clay (< 2 µm)	17.1	17.9	22.2	
SOC (0-20 cm; g m^{-2})				
No-tillage (NT)	2942	3111	2743[§]	2306[‡]
Reduced tillage (RT)	–	2876	2285	2154
Subsoil tillage (ST)	2947	2592	–	–
Conventional tillage (CT)	2869	2541	2278	2021

[¶] USDA classification (Soil Survey Staff, 1975).
[§] SOC in PN-CC (Peñaflor site under continuous cropping system).
[‡] SOC in PN-CF (Peñaflor site under cereal-fallow rotation)

Table 2. Total monthly precipitation (P) and mean monthly air temperature (T) recorded at the three experimental sites in 2003, 2004 and 2005.

	Selvanera						Agramunt						Peñaflor					
	2003		2004		2005		2003		2004		2005		2003		2004		2005	
	P (mm)	T (ºC)	P (mm)	T (ºC)	P (mm)	T (ºC)	P (mm)	T (ºC)	P (mm)	T (ºC)	P (mm)	T (ºC)	P (mm)	T (ºC)	P (mm)	T (ºC)	P (mm)	T (ºC)
January	17	2.8	3	4.9	0	0.6	18	2.9	6	5.0	1	1.2	32	5.8	10	7.6	2	3.6
February	58	0.8	44	3.7	5	2.4	70	4.8	43	4.4	1	3.0	41	6.0	43	4.7	7	4.2
March	8	9.6	39	7.0	9	10.0	22	0.0	47	7.7	2	9.1	37	11.0	56	7.9	7	9.6
April	16	11.8	66	10.4	11	12.5	20	13.3	61	11.1	2	13.6	32	13.4	42	11.2	16	13.7
May	38	16.8	83	16.6	44	18.3	46	17.6	67	16.0	8	19.1	69	17.5	35	15.9	49	18.4
June	11	24.6	15	23.2	30	23.6	2	26.2	18	22.9	1	24.3	27	25.6	6	23.6	45	23.8
July	20	25.0	53	24.1	2	27.2	5	26.4	28	24.0	0	25.6	1	25.9	15	23.9	0	24.8
August	12	26.2	38	24.4	28	22.6	12	27.9	22	24.5	5	23.0	10	26.9	11	24.2	4	23.3
September	141	19.0	22	23.8	50	26.0	110	19.4	1	20.9	4	19.2	66	19.6	25	21.1	29	19.9
October	94	13.1	23	24.5	54	15.7	107	12.8	23	14.4	70	15.3	61	14.2	33	16.6	46	15.9
November	34	8.8	3	14.5	43	7.9	46	8.8	3	6.0	62	7.4	48	9.9	9	7.7	22	8.8
December	49	4.4	33	4.6	10	0.1	43	4.9	41	4.7	8	3.9	19	6.6	33	6.8	9	3.0
Year	*498*	*13.6*	*422*	*15.1*	*286*	*13.9*	*501*	*13.7*	*360*	*13.5*	*164*	*13.7*	*443*	*15.2*	*318*	*14.3*	*236*	*14.1*

Table 3. Schedule of soil CO_2 measurements for each experimental site (SV, Selvanera site under a wheat-barley-wheat-rapeseed rotation; AG, Agramunt site under a barley-wheat rotation; PN-CC, Peñaflor site under continuous cropping and PN-CF, Peñaflor site under cereal-fallow rotation) and tillage treatment (CT, conventional tillage; ST, subsoil tillage; RT, reduced tillage; NT, no-tillage).

Experimental field	Tillage treatment	Tillage date	Measurements since 1st tillage (hours)†
SV	CT, ST	22 July 2003 (1st tillage)	-24, 0, 3, 6, 24, 48
	CT, ST	10 August 2004 (1st tillage)	-24, 0, 3, 24, 48
AG	CT, ST, RT	21 November 2003 (1st tillage)	-24, 0, 3, 6, 24, 48
	CT, ST, RT	11 November 2004 (1st tillage)	-24,0, 3, 6, 24, 48
PN-CC	CT, RT	25 November 2003 (1st tillage)	-24, 0, 3, 6, 24, 48
	CT, RT	2 December 2003 (rotovator pass)	144, 168, 171, 192
PN-CC	CT, RT	10 November 2004 (1st tillage)	-24, 0, 3, 6, 24
PN-CF	CT, RT	19 March 2003 (1st tillage)	-24, 0, 6, 24, 48, 264
	CT	7 April 2003 (clod crusher)	384, 408, 414, 432
PN-CF	CT, RT	9 March 2005 (1st tillage)	-24, 0,
	CT	9 March 2005 (clod crusher)	1, 3, 6, 24, 48

† Measurements were also made in the NT plots.

Table 4. Determination coefficients (R^2) between soil CO_2 fluxes and abiotic factors (soil temperature and gravimetric water content) per each site (SV, Selvanera site under a wheat-barley-wheat-rapeseed rotation; AG, Agramunt site under a barley-wheat rotation; PN-CC, Peñaflor site under continuous cropping and PN-CF, Peñaflor site under cereal-fallow rotation) and tillage event.

Abiotic factors	SV		AG		PN-CC		PN-CF	
	2003	2004	2003	2004	2003	2004	2003	2005
Soil temperature	0.190	0.067	0.250*	0.170	0.100	0.230	0.002	0.012
Soil water content	0.032	0.170	0.060	0.001	0.004	0.033	0.018	0.190

* R^2 significant at 0.10 level of probability .

Table 5. Cumulative CO_2 emissions during the first 48 h following tillage (CT, conventional tillage; ST, subsoil tillage; RT, reduced tillage; NT, no-tillage) at Selvanera (SV) under a wheat-barley-wheat-rapeseed rotation, Agramunt (AG) under a barley-wheat rotation and Peñaflor under continuous cropping (PN-CC) and a barley-fallow rotation (PN-CF).

Site and measurement period	Cumulative CO_2 emissions (g CO_2 m^{-2})			
	NT	RT	ST	CT
SV 2003	37	-	72	78
SV 2004	140	-	273	287
AG 2003	48	78	82	97
AG 2004	24	31	34	45
PN-CC 2003	34	46	-	58
PN-CC 2004	12	21	-	27
PN-CF 2003	4	6	-	10
PN-CF 2005	6	10	-	16